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W/SiC and Pt/SiC multilayers for the NuSTAR hard x-ray telescope

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Abstract

This paper will discuss the coatings for the Nuclear Spectroscopic Telescope Array (NuSTAR) and describe the updates of the coating facility at the Danish National Space Center, necessary to make all the coatings in the required time frame. The inner part of the three NuSTAR telescopes will be coated with Pt/SiC and the outer part with W/SiC. To understand the roughness of the flight coatings, we will present results from 10 bilayer constant *d*-spacing coatings for both types of flight coatings. Also, data showing the homogeneity over the octant mirror segments as well as X-ray data from realistic depth graded coatings will be presented. The long time stability and stress in the coatings will be discussed.

Keywords: NuSTAR. hard X-ray telescope, multilayer coating

1. Introduction

After finishing coating the optic for the High Energy Focusing Telescope[1] (HEFT) balloon payload, which had a successful flight in spring 2005, the production facility at Danish National Space Center (DNSC) is being upgraded for the coating of the optic for the Nuclear Spectroscopic Telescope Array (NuSTAR). NuSTAR is a hard x-ray focusing telescope mission designed to focus and image X-ray energies between 8 keV and 80 keV. The primary science goals are to study galactic and extragalactic black holes, Ti-44 line emission in young supernova remnants, and make spectral and time-variability studies of active galactic nuclei. The satellite is in an extended phase A study as a NASA SMEX mission and is a collaboration between Caltech, Jet Propulsion Laboratory, Columbia University, Danish National Space Center, Lawrence Livermore National Laboratory, Stanford Linear Accelerator Center, U. C. Santa Cruz, Sonoma State University, General Dynamics Spectrum Astro, and ATK. NuSTAR is scheduled to fly in 2009.

NuSTAR will fly three telescopes. However, instead of 72 mirror shells packed inside a radius between 40 mm and 120 mm as on HEFT, NuSTAR will have 130 shells lying between a radius of 54.9 mm and 168.6 mm. On HEFT the optic design is a conical approximation to a Wolter-I. Both the upper and lower reflectors are separate and divided in quintants, resulting in 1440 pieces of glass for each telescope. On NuSTAR the optics will be divided in octants for performance reasons, which gives 4160 pieces of glass for each telescope. HEFT was build using 0.3 mm thermally slumped glass where NuSTAR will use 0.2 mm thermally slumped glass to save weight. With three flight telescopes, a spare telescope, and a reasonable safety margin an estimate of up to 30000 pieces of glass have to be coated in a 2 year time frame. To do this the coating facility at DNSC and the coating technology has been updated. For a more complete discussion about NuSTAR refer to Koglin et. Al[2].

The chamber, as seen in fig. 1, now includes 4 planar magnetron sputter cathodes with the possibility to run any given combination of cathodes in one run. Previously there were only two in the chamber while HEFT was produced. To further decrease the coating time for each run, the old cathodes will be upgraded to longer ones. Presently there are three cathodes of the old design with a target size of 508 mm x 38 mm x 3.2 mm, the cathode size used for HEFT, and one of the new design with target size of 660 mm x 63 mmx 3.2 mm in the chamber. Before starting the production coatings for NuSTAR all four cathodes will be of the new design. The chamber is made ready for the new cathodes so they can easily be swapped around with the old ones when they arrive and with the possibility to go back to the old ones if desired. With longer cathodes more mirrors can be coated in one run and with the additional and wider cathodes the coating time per layer be reduced. Also a new ring for the sample mounting plates has been designed as well as new

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Fig. 1. Looking down into the multilayer coating facility with four DC magnetron sources, one new (in center) and three old all separated with 90° in between. The shutters are open on three of the cathodes and closed on the one to the left. The big ring holding the sample mounting plates, half of which has been removed to give a better view, is one meter in diameter. Everything is made ready to replace the old cathodes when the new and bigger ones arrive.

mounting plates. In the old system there are 16 mounting plates, 600 mm tall and 150 mm wide, and 2 dummy plates. Using the new mounting ring there will be 18 mounting plates, which will be 800 mm tall and 125 mm vide, and 3 dummy plates. The presence of dummy plates is to prevent sputtering the glass when opening and closing the shutters and accelerating the ring to the desired speed. Because the length of each piece of glass in the direction of the optical axis is 100 mm (it is mounted with the optical axes horizontal in the chamber) the width of the mounting plates can be reduced, giving space for extra sample mounting plates. With the new mounting plates installed we will be able to coat 0.8 m^2 per run. For NuSTAR the requirement is 1.9 m^2 per week so there is a good capacity margin.

When coating the flight optic for HEFT the two cathodes were coating at the same time, so that one rotation of the sample mounting ring resulted in one full bilayer on all the mirrors. The fractional bilayer thickness, Γ, was controlled by applying the maximum power to the slowest coating material and adjusting the power to the other cathode[3]. When coating the NuSTAR optic the plan is to use three cathodes at the same time. Two cathodes coating the slowest coating material and then increase the power on the third cathode resulting in the desired gamma. This way we are decreasing the coating time to half of what it would have been for a two-cathode setup. The reason for not coating with all four cathodes is that it would decrease the numbers of sample mounting plates (one extra dummy plate) but we would still only be able to make one coating per day and therefore the overall throughput would decrease. The chamber is opened during the day for cleaning, taking out the coated glass, and installing new ones. This takes between one and two hours. The time for pumping down the chamber to below $2.6*10^{-4}$ Pa ($2*10^{-6}$ Torr) takes between 4 and 6 hours and the coating time is between 7 and 11 hours. Normally we first start coating when the pressure is below $1.3*10^{-4}$ Pa ($1*10^{-6}$ Torr), the background pressure in the chamber is better than $4*10^{-5}$ Pa ($3*10^{-7}$ Torr). Meanwhile the chamber is being evacuated for coating, the next day mirrors are cleaned and mounted on another set of mounting plates ready to put into the chamber. Having four cathodes in the chamber allows us to move things around and therefore decrease the down time in the case of any problems that will occur during a production with a tight time schedule.

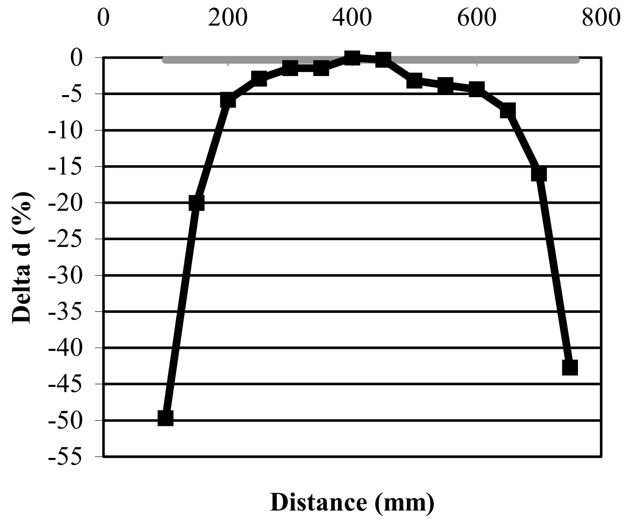


Fig. 2. Delta *d,* the variation between the coating thickness and the thickest coating on the sample mounting plate in percent. There is with the current mask an area of 300 mm where the thickness variation is below ± 2 % and an area of 450 mm where the thickness variation is below ± 4 %. The gray line shows the length of the mask.

The coatings on both HEFT and NuSTAR are depth graded multilayers. The specific multilayer design depends on graze angle that scales with the optic radius. Therefore the 130 shells are divided into 20 mirror groups and the multilayer design on each mirror group is optimized. The inner 14 mirror groups (90 shells) are coated with Pt/SiC and the outer 6 mirror groups (40 shells) are coated with W/SiC. The HEFT optics are coated with W/Si on all the telescopes.

In this paper we will describe the different updates done to the chamber and the new coating setup. We will also present data for the homogeneity of the coatings in the new setup, the stress and some data demonstrating the long time stability of the coatings. All x-ray measurements in this paper are done at 8 keV and all modeling of X-ray data are done using IMD[4].

2. Masking and collimation of cathode

To be able to coat a large amount of glass in a single run and having a high degree of homogeneity between the different pieces of glass along a mounting plate, a large area of the cathode is required to have the same constant coating rate. The coating rate from point to point on the sample mounting plate will be effected by the finite length of the cathodes[5] and effects corresponding to the variations of the magnetic field along the magnets. For the old cathodes there are only an area of about 150 mm with homogeneity in the coating rate without any mask but using an experimentally designed mask there are an area of 300 mm where the thickness variation is below ± 2 % and an area of 350 with a thickness variation below ± 3 %. The masks were designed by placing a lot of Si samples along a sample mounting plate and then coat a 10 bilayer W/Si coating. After plotting the thickness variation (gamma were constant with very small variations) a new sets of masks could be made and by iteration the final mask were designed. One of the reasons to get new bigger cathodes was to increase the area with a homogenious coating area. The new cathodes are 150 mm taller than the old once. Since we only have one of the new cathodes the preliminary mask design for this have been done using a single layer W coating. Fig. 2 shows the thickness variation along a sample mounting plate using a mask on the new cathode. The area where the thickness variation is below ± 2 % is 300 mm and there is an area that is 450 mm where the thickness variation is below ± 4 %. Outside this area the thickness variation increase a lot due to the finite length of the cathode. The plan is to further modify the mask (the mask length is indicated with the gray line in fig. 2) but the final design can first be done when we have all the new cathodes. The target sample distance is 128 mm and the mask is 48 mm from the target.

When we were coating HEFT we were using 50 mm wide separator plates between each mirror both for collimation and to control the coating thickness over the curved sample[3]. During a coating the ejected atoms from the target will follow a distribution of straight lines from every single point on the target if there were no interaction with the sputtering gas[6]. Since there is an interaction, especially for the light atoms, the atoms will arrive to the substrate with less energy resulting in a rougher coating. Therefore one reason to use separator plates was to collimate the material and the other was to control the coating thickness. The closer a substrate is to the cathode the thicker the coating will be compared to the substrate further away. Since the substrates on HEFT were quintents some places on the substrate were much closer to the cathodes than the center of the substrate. By using separator plates the shadow effect from the plates compensated for this effect.

For NuSTAR we have chosen another concept for collimation than the separator plates. In front of the cathode (50 mm away from the cathode) we have installed a mesh of honeycomb. The dimension of the honeycomb is from edge to edge 6.4 mm and the depth is 5 mm. This grid midway between the target and the substrate block atoms that are not traveling near perpendicular from the target to the substrate and we collimate that way the coated material resulting in a less rough coating. The dimensions of the honeycomb define the degree of collimation and it is important that the honeycomb is electrically floating during the whole coating process since it otherwise destabilizes the plasma. Since NuSTAR is using octants and not quintants as HEFT the height difference on each piece of glass will be much smaller and we will not need the shadow effect from the separator plates (it may be still be necessary to use separator plates for the outer most glass). The advantage in not using separator plates is that we can pack more glass in one run. Using separator plates there were between 10 mm and 20 mm between the glass and the separator plates so for each piece of glass we lost 20 mm to 40 mm of active area on the mounting plates. Without the separator plates the glass can be mounted next to each other using basically all the area on each mounting plate.

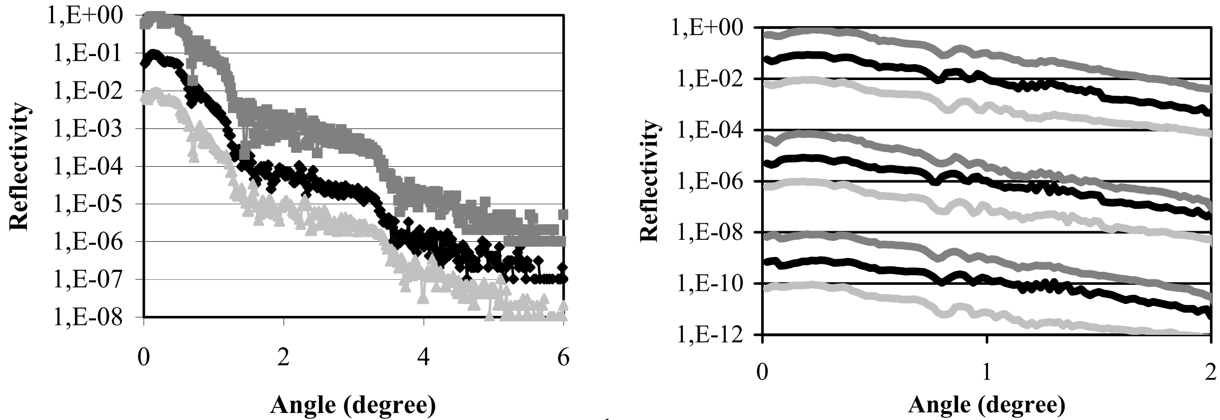
3. Coatings using Pt/SiC and W/SiC

The roughness of the coatings has a huge effect on throughput and image quality of the final telescope. Therefore to evaluate different material combinations we have made 10 bilayer constant *d*-spacing coatings on Si wafers with *d*-spacing from 2.0 nm and up to 20.0 nm. We use Si wafers as substrate to compare the roughness of the different material combinations since the wafers have a constant roughness from wafer to wafer on order 0.25 nm, whereas the roughness on the slumped glass is varying but are on average 0.35 nm.

The HEFT optics was optimized for energies between 20 keV and 70 keV, just to the W k-absorption edge at 69.8 keV and were coated using W and Si. NuSTAR is designed for energies between 8 keV and 80 keV. Therefore to get a good throughput from 69 to 80 keV we use Pt instead of W for the inner mirrors on the telescope. For larger grazing incidence angles where the high-energy response is low, W still provides a better low energy response than Pt, and the outer shells therefore are coated with W.

For 10 bilayer W/Si constant *d*-spacing coatings on Si-wafers the roughness are on average 0.33 nm for coatings with *d*-spacing between 2.0 nm and up to 10.0 nm, and increasing to 0.35 nm for the thickest coatings up to 20.0 nm. For a graded flight coating on thermally slumped glass the roughness is around 0.35 nm. By replacing the Si with SiC the roughness of the constant *d*-spacing coatings on Si-wafers, with *d*-spacing between 2.0 nm and 10.0 nm, were reduced to 0.29 nm. For the thicker coatings it was a little higher, but still below 0.32 nm. We obviously don't have as good a statistic for W/SiC coatings on thermally slumped glass as we have for W/Si of which we have coated on the order of 10000 pieces, but so far the roughness of realistic flight coatings on thermally slumped glass have yielded a roughness of 0.30 nm. Since the optical constants for Si and C are very close, the change of spacer material from Si to SiC does not result in any unwanted reflectivity effects.

The decrease in roughness from 0.35 nm to 0.30 nm is significant and increases the effective area of the optics. The scatter in the flight coatings is at the moment dominated by the figure error of the substrates, but with better substrates



a b

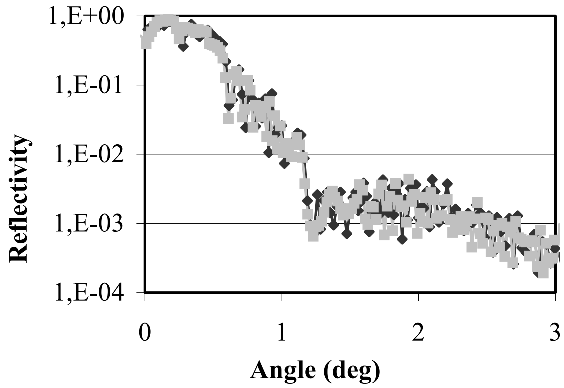
Fig. 3. a: 40 bilayer graded Pt/SiC coating on thermally slumped glass with radius 75 mm. b: 233 bilayer graded W/SiC coating on thermally slumped glass with radius 115 mm. a+b: The reflectivity as function of gracing incidence angle measured on nine (three for Pt/SiC) different positions. The curves are shifted in the y-direction for clarity but no shift has been made in the horizontal direction. The center of the sample is defined as 0 mm length and 0 degrees in azimuth angle. The black lines are measured at 0 degree azimuthally, the dark gray at +20 degree, and the light gray at -20 degree at there different length on the optical axes. The top three lines are measured at 30 mm from the center, the center three lines are measured at the center and the three last lines are measured at -30 mm. For Pt/SiC it is the scans for length 0 that is shown.

higher specular reflectivity will also effectively decrease the scatter. This may ultimately be important for future missions such as XEUS.

On InFOCUS the mirrors were coated with Pt/C[7]. We have alternatively developed Pt/SiC coatings. Coating constant *d*-spacing coatings on Si wafers with Pt/SiC gave roughness of 0.32 nm for coatings with bilayer thickness between 2.0 nm and 10.0 nm and roughness of 0.36 nm for the thick coatings up to 20.0 nm. Realistic graded flight coatings with Pt/SiC on thermally slumped glass gave roughness around 0.37 nm. The baseline roughness parameter used for the proposal of NuSTAR is 0.40 nm for Pt/SiC and 0.35 nm for W/SiC.

To evaluate the effect on the octant mirrors when not using separator plates we have made constant *d*-spacing coatings on thermally slumped glass. The thickness was measured 9 different places on the thermally slumped glass. The center of the sample is defined as 0 mm length and 0 degrees in azimuth angle. We made measurements at 0 degree and ± 20 degrees (along the substrates curvature) and for lengths 0 and length ± 30 mm (along the substrates optical axe). For a 10 bilayer Pt/SiC coating on a thermally slumped glass with radius 75 mm the thickness variation over the glass was ± 1.1 %. For a glass with radius of 115 mm and with W/SiC coating the thickness variation over the glass was ± 1.8 %. Since the thickness variation over the thermally slumped glass will increase when we come to the outer most glass on the telescope we expect to use separator plates for these mirrors.

In fig. 3a is shown reflectivity measurements of a depth graded Pt/SiC coating with 40 bilayer measured in the center of the thermal slumped glass and at ± 20 degrees. It is seen that even though there is a small variation in the coating thickness over the glass it is so small that it have very little influence on the reflectivity curve of the graded coating. In fig. 3b are the reflectivity measurement from 9 different places on a thermal slumped glass with radius of 115 mm and coated with a 233 bilayer depth grated W/SiC coating. The data have been shifted vertically but no shift has been done in the horizontal direction. It is seen that there is only a very small difference in the reflectivity curves over the sample and the small shift that can be seen between the curve in the center of the glass and the ± 20 degrees correspond to a very small shift in *d*-spacing. The thickness variation will be bigger on the bigger radius mirrors than the ± 1.8 % we



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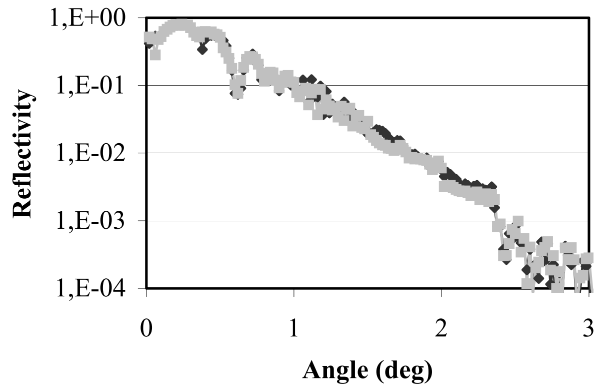

b

Fig. 4. a: 50 [Pt/SiC] graded *d*-spacing coating. The dark gay points are measured just after the coating was done in June 2004 and the light gray is measured in June 2005. b: 291[W/SiC] graded *d*-spacing coating. The dark gay points are measured just after the coating was done in February 2004 and the light gray is measured in June 2005.

have for radius 115 mm and then the effect on the depth graded coating will be more pronounced. This is why we will need to use the separator plates for these radii.

4. Stability and stress

To demonstrate the long-term stability of the coatings we have remeasured two coatings that have been stored in a normal laboratory environment. Fig 4a shows a 50 bilayer depth grated Pt/SiC coating measured just after production and a year later. As it is seen there is no degradation of the coating over that year. We see a very small change for the 291 bilayer W/SiC coating over 16 month between the two measurements in the area between 1.5 degree and 2.3 degree but this variation is small and could easily be explained by measuring on a slightly different spot on the sample.

To further understand the stability of the coatings we have had stress measurements made on some of our coatings[8]. We did a 50 bilayer Pt/SiC coating with a total thickness of 300 nm and found that the compressive stress were -351 Mpa. We also compared two samples both made with the same 291 bilayer coating, one with W/SiC and one with W/Si, both with a total thickness of 888 nm. The W/SiC coating had the highest compressive stress (–285 Mpa) where the W/Si coating had –25 Mpa. The –25 Mpa is very low and the stress level of the Pt/SiC and the W/SiC is not a problem. We also made stress measurements on samples coated with the same W/SiC and W/Si coatings as above but instead of using honeycomb we used separator plates. This gave for W/SiC –315 Mpa and for W/Si –76 Mpa, showing that the use of honeycomb reduces the stress in the coating.

5. Summary

In this paper we have discussed the coating of the optic to the NuSTAR telescope and shown the upgrade done to the coating facility at DNSC to accomplish the task in the required time frame.

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